



Performance Sensitivity Studies on the PIAA Implementation of the High-Contrast Imaging Testbed

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Beginning Remarks

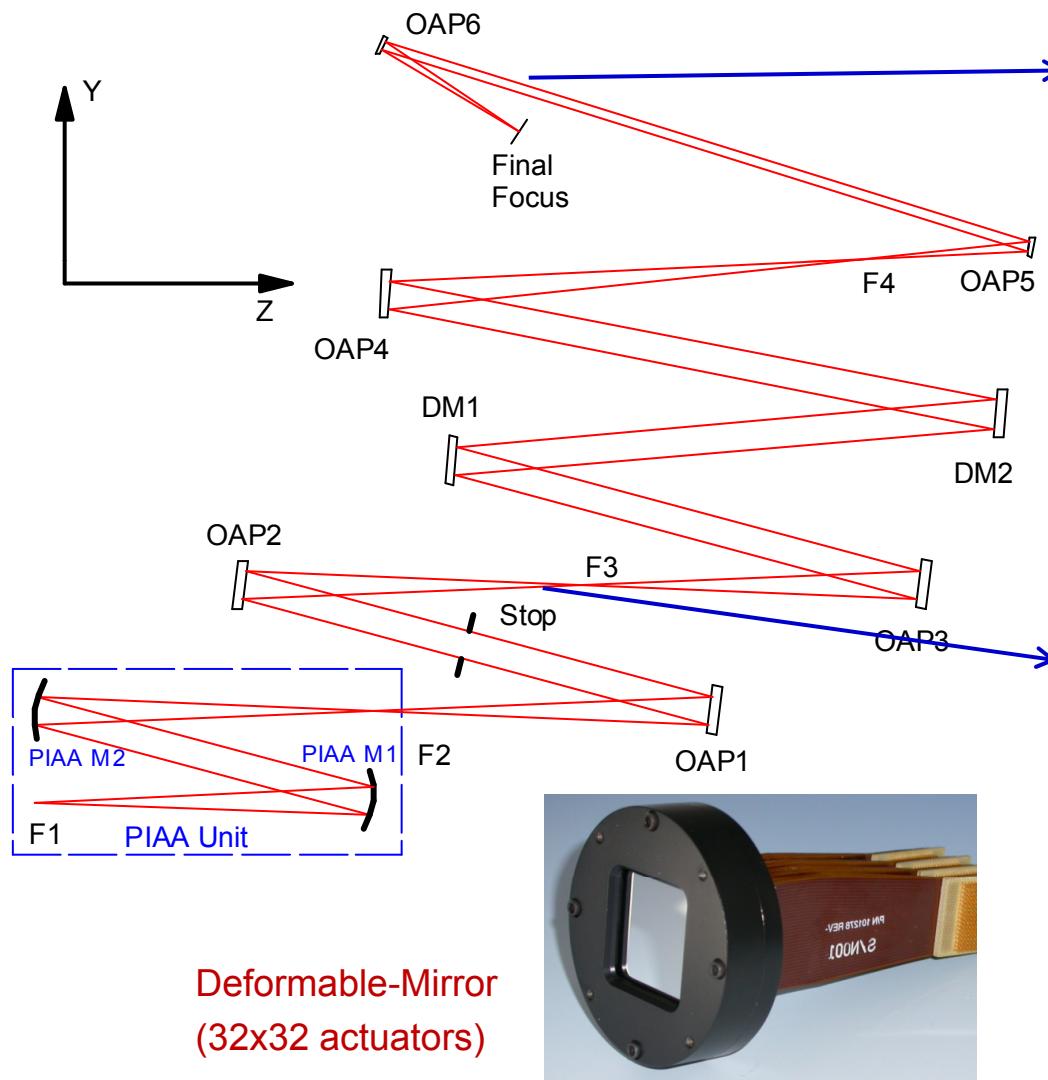
- Phase-Induced Amplitude Apodization (PIAA), or pupil mapping, is a promising technique in high-dynamic range stellar coronagraph. As compared to other designs, it provides
 - Higher throughput
 - Better inner working angle
- One of the High-Contrast Imaging Testbed implementations use a PIAA unit at its input and 2 DMs in series
- Want to validate the PIAA/HCIT hybrid system's performance through modeling and error budget analysis
- Have implemented a MACOS-based simulation algorithm which
 - combines a ray trace, diffraction model, & a broadband wavefront control algorithm
 - is capable of performing full three-dimensional near-field diffraction analysis
- In this paper, we investigate the effects of the phase and rigid-body errors of various optics on the narrowband contrast performance of the PIAA/HCIT hybrid system

Optical Layout

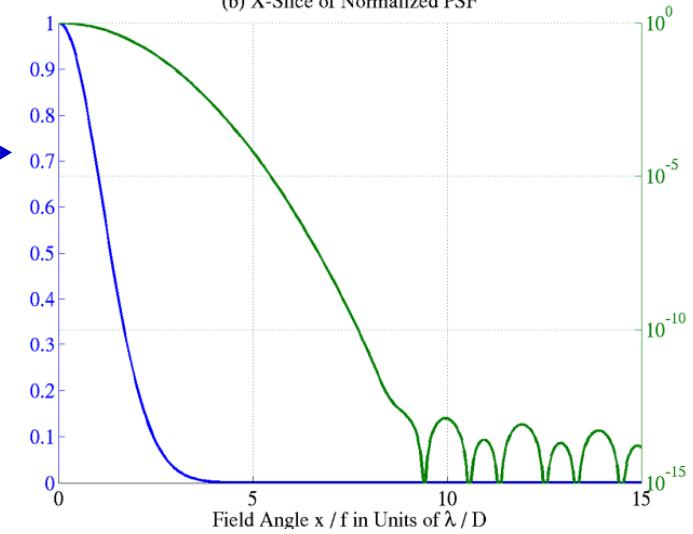
PIAA: IWA slightly larger than $2 \lambda/D$ on the sky

STOP Aperture D = 25.7mm

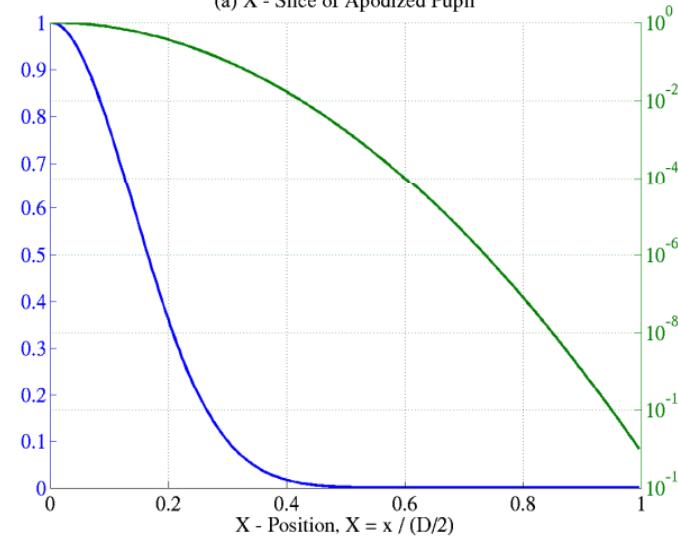
$\lambda = 800\text{nm}$



(b) X-Slice of Normalized PSF



(a) X - Slice of Apodized Pupil

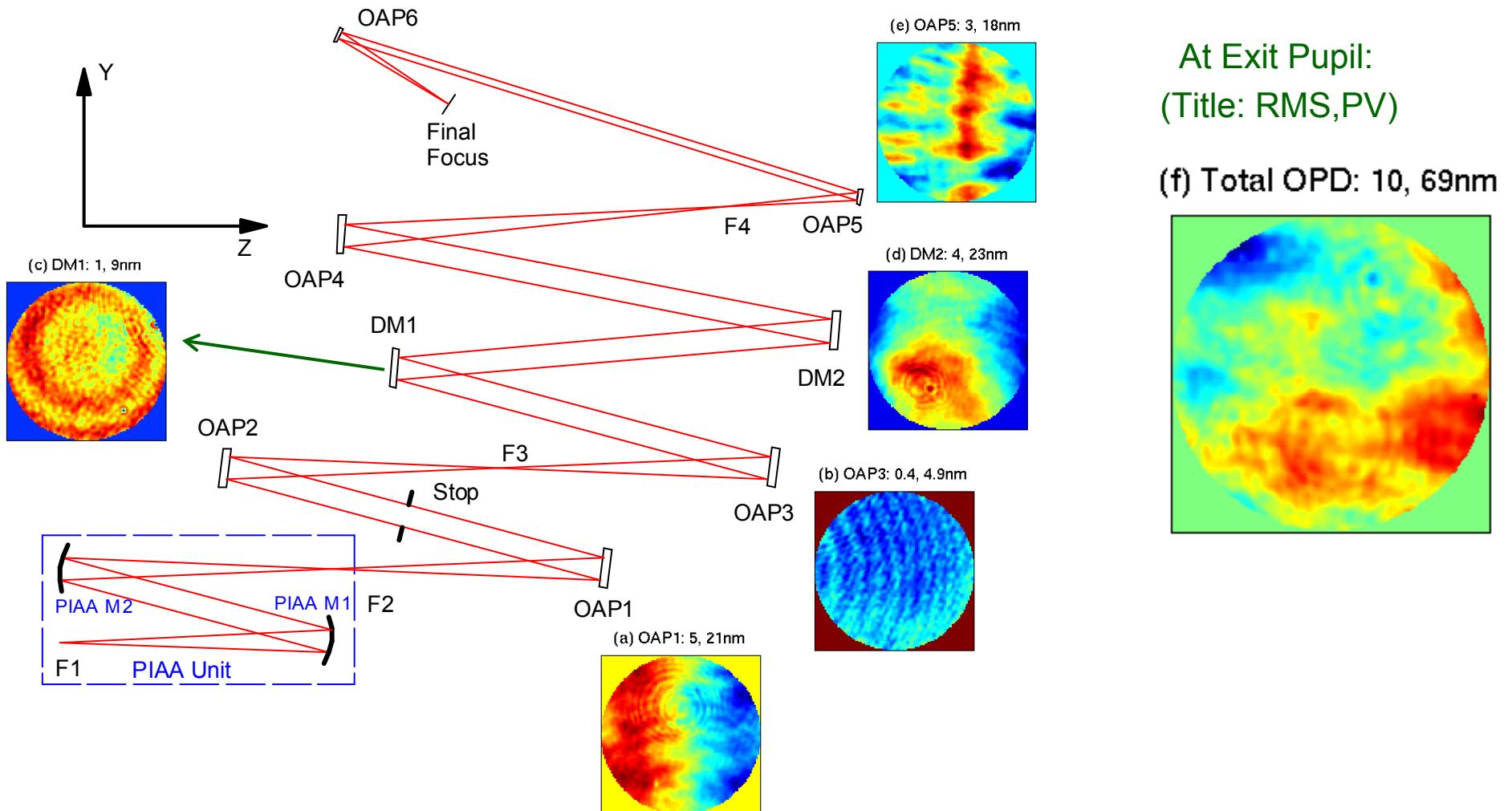


3

Designed by O. Guyon, Subaru Telescope

Surface Errors Assumed in Analysis

Surface error maps were obtained previously from measurement of former HCIT optics



Wavefront Control Algorithm

Correction of e-field: Borde & Traub 2006; Give'on et al 2007

$$E(m, n) = a(m, n) + i b(m, n) \quad \text{e-field inside } \Omega$$

$$\bar{\mathbf{e}} = \begin{bmatrix} \vec{\mathbf{a}}' \\ \vec{\mathbf{b}}' \end{bmatrix} \quad \text{e-field vector arranged in certain order}$$

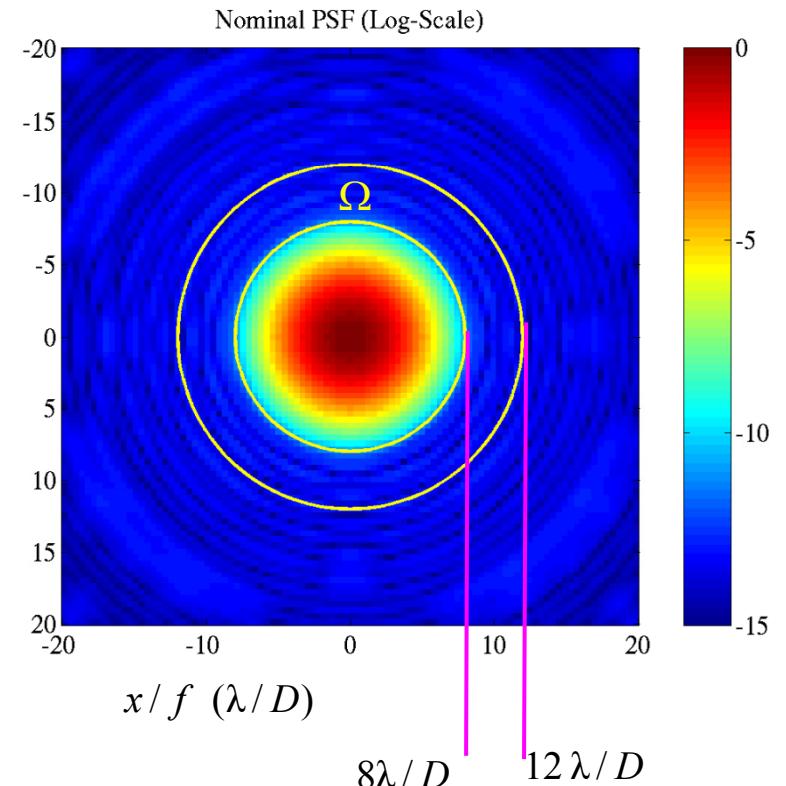
$$\bar{\mathbf{s}}_i = \frac{\bar{\mathbf{e}}_i - \bar{\mathbf{e}}_0}{u_i - u_{i0}} \quad \text{Sensitivity vector, } \mathbf{u} = \text{act. command}$$

$$\tilde{\mathbf{S}} = [\bar{\mathbf{s}}_1 \quad \bar{\mathbf{s}}_2 \quad \dots \quad \bar{\mathbf{s}}_N] \quad \text{Sensitivity matrix (Influence Func.)}$$

$$\tilde{\mathbf{G}} = \text{pinv}(\tilde{\mathbf{S}}, \text{tol}) \quad \text{Gain matrix (Least-square compensator with a tolerance)}$$

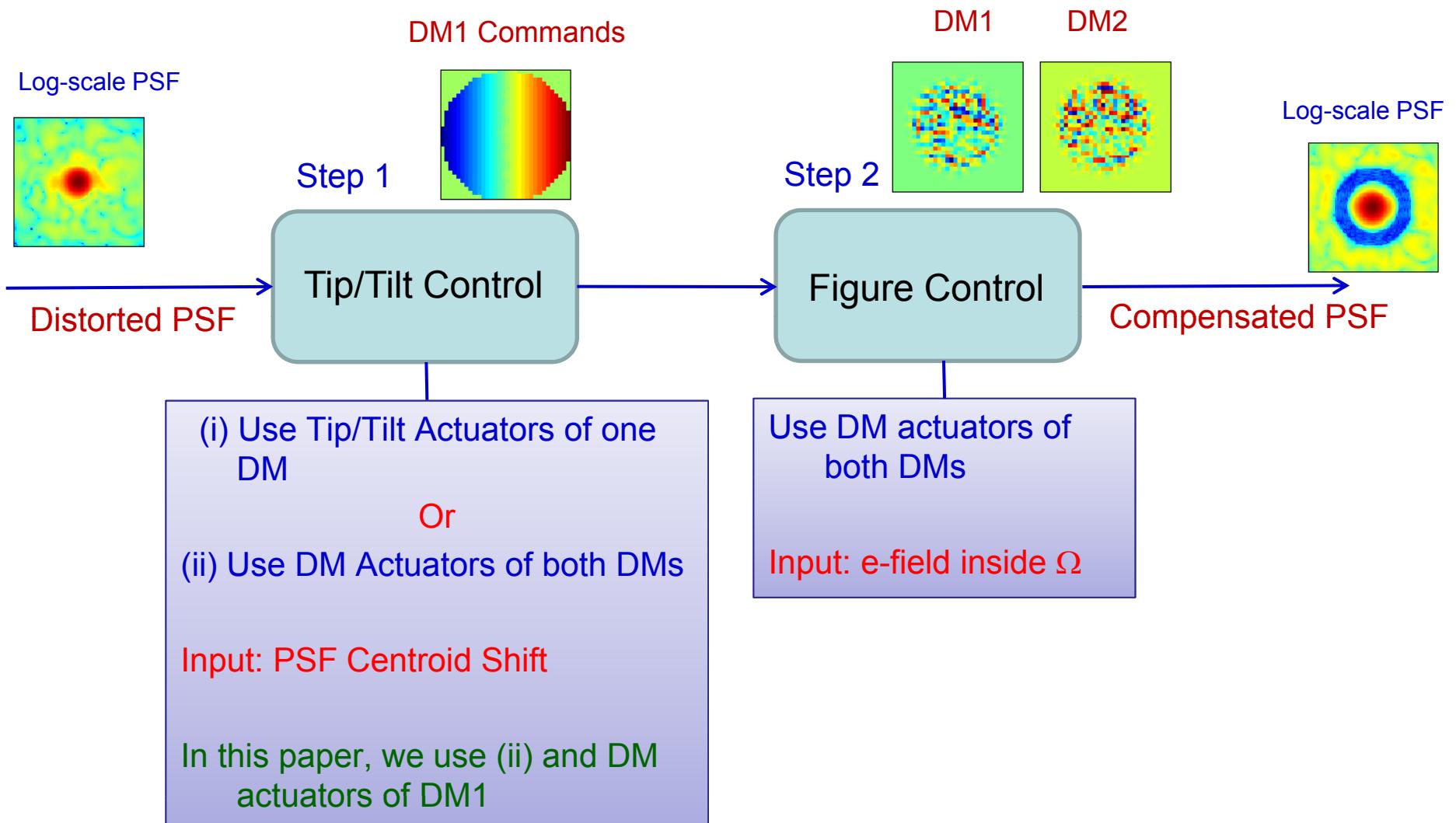
$$\tilde{\mathbf{G}} = \left[(\tilde{\mathbf{S}}^T \tilde{\mathbf{S}})^{-1} + \gamma_{\text{eu}} \tilde{\mathbf{I}} \right] \tilde{\mathbf{S}}^T \quad \text{Gain matrix (Actuator regularization)}$$

$$\vec{\mathbf{u}}_{i+1} = \vec{\mathbf{u}}_i - \tilde{\mathbf{G}} \times \vec{\mathbf{e}}_i \quad \text{Actuator commands}$$



Actuator Number:
 $N = 2048$ (Total)
 $N' = 1268$ (Used)

Two-Step Wavefront Control Approach



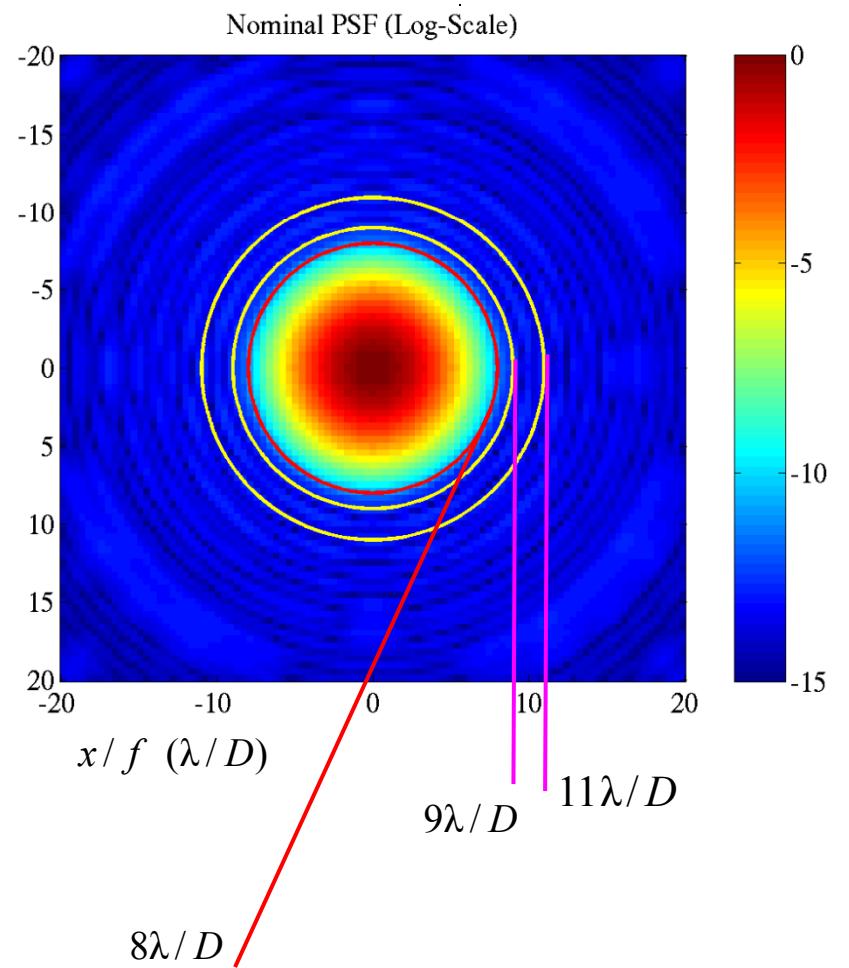
Three Contrast Parameters to be Tracked

C_b = Mean contrast: $9 \lambda/D - 11 \lambda/D$ (b = “Big”)

C_s = Mean contrast: $8 \lambda/D - 9 \lambda/D$ (s = “Small”)

C_m = Max contrast: $8 \lambda/D - 9 \lambda/D$ (m = “Max”)

E-field control region: $8 \lambda/D - 12 \lambda/D$



DM Actuators Used

Each DM has 32x32 actuators:

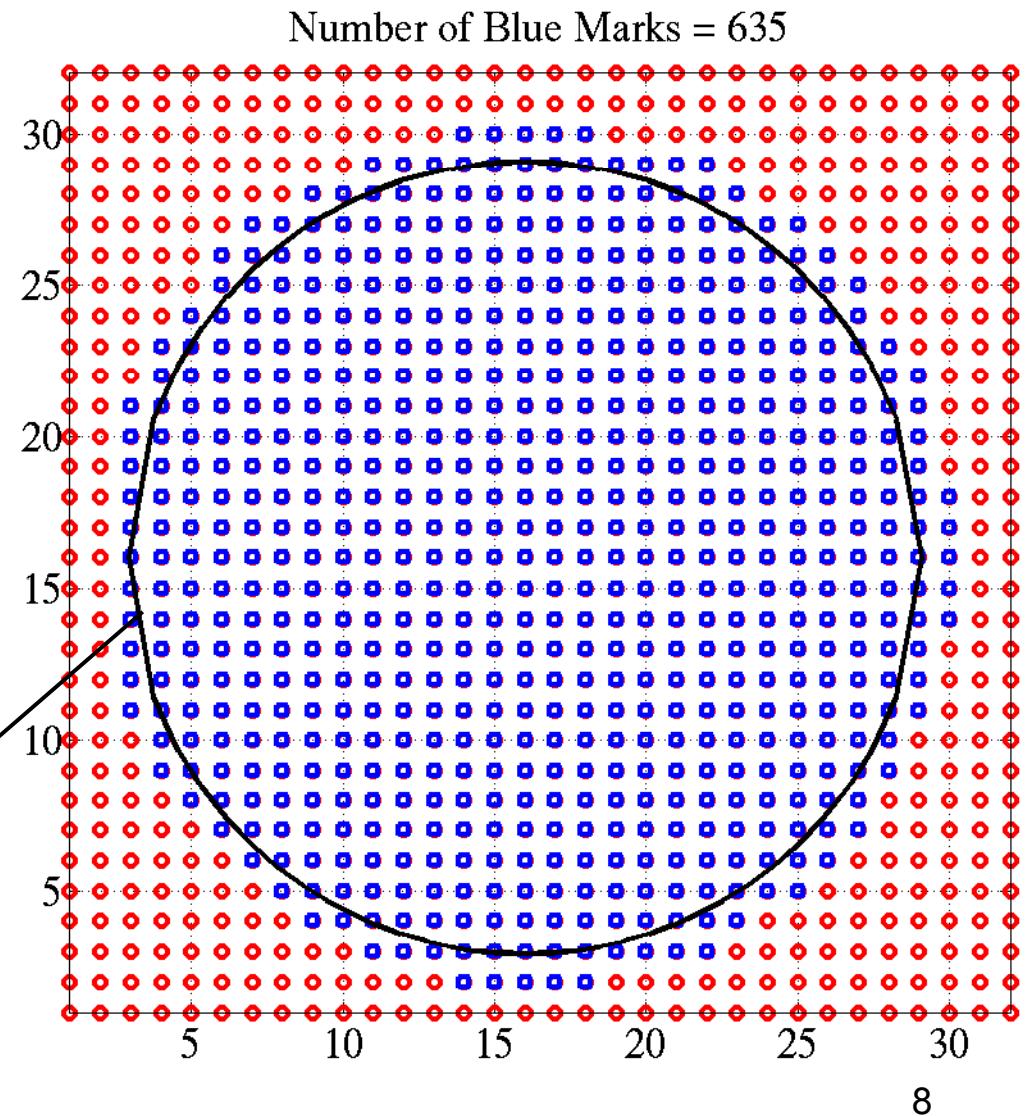
Total # = 1024

Number of Actuators Used:

DM1 = 635

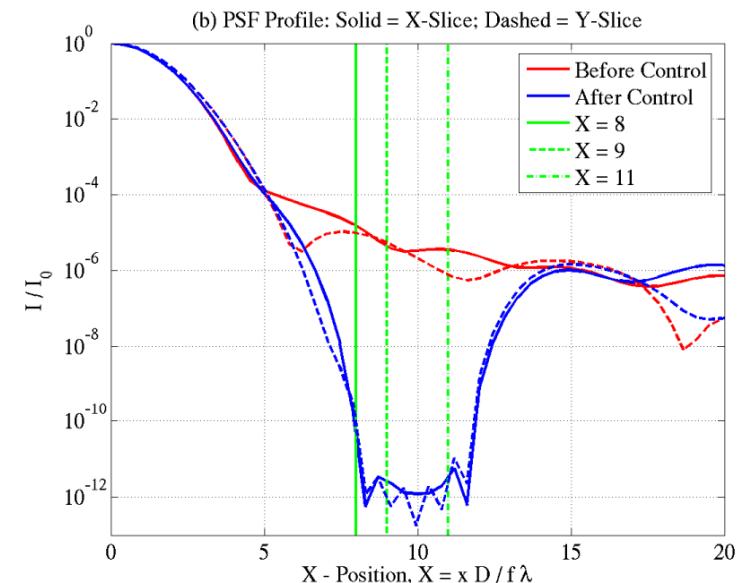
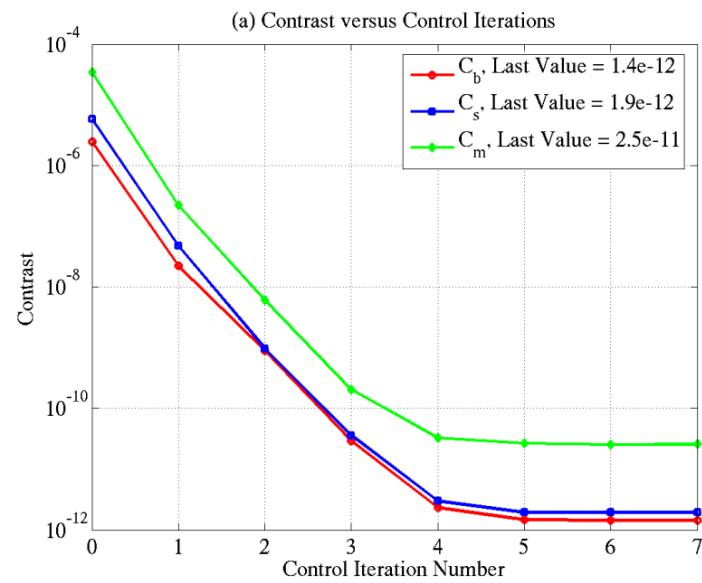
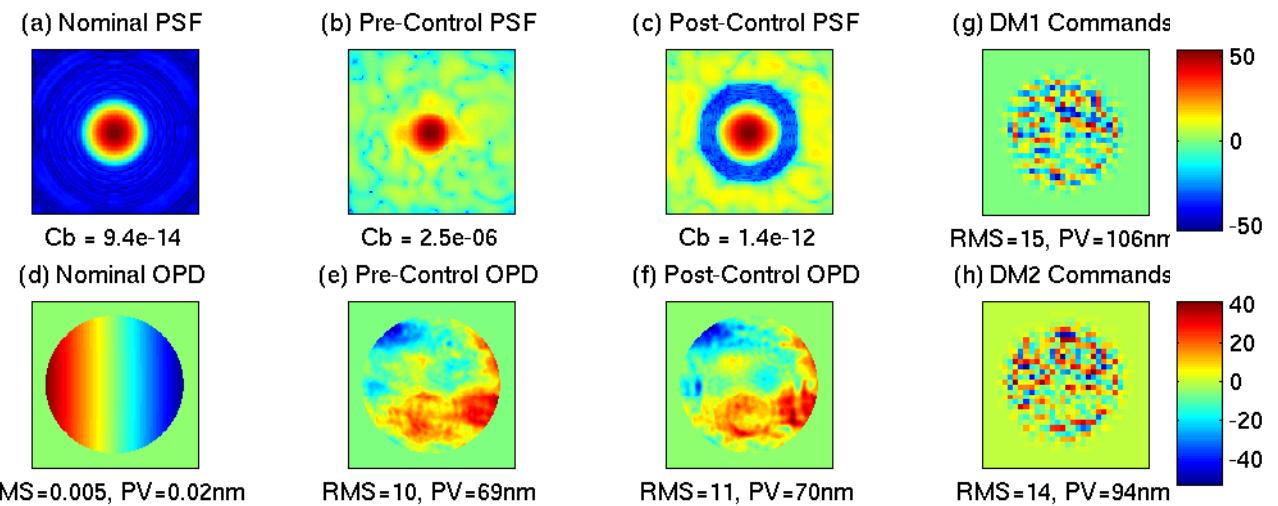
DM2 = 633

Rough boundary of beam foot-print

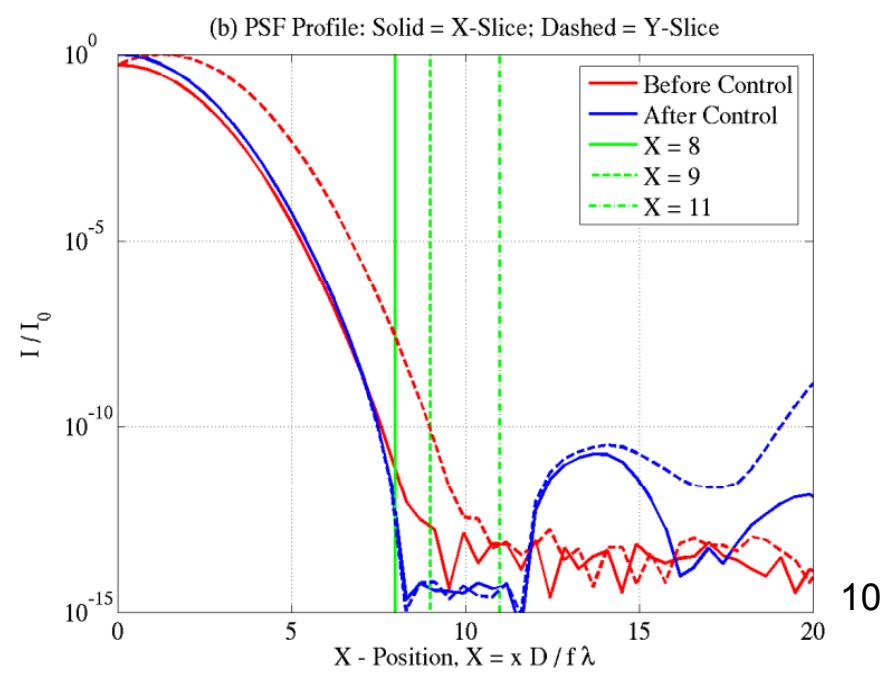
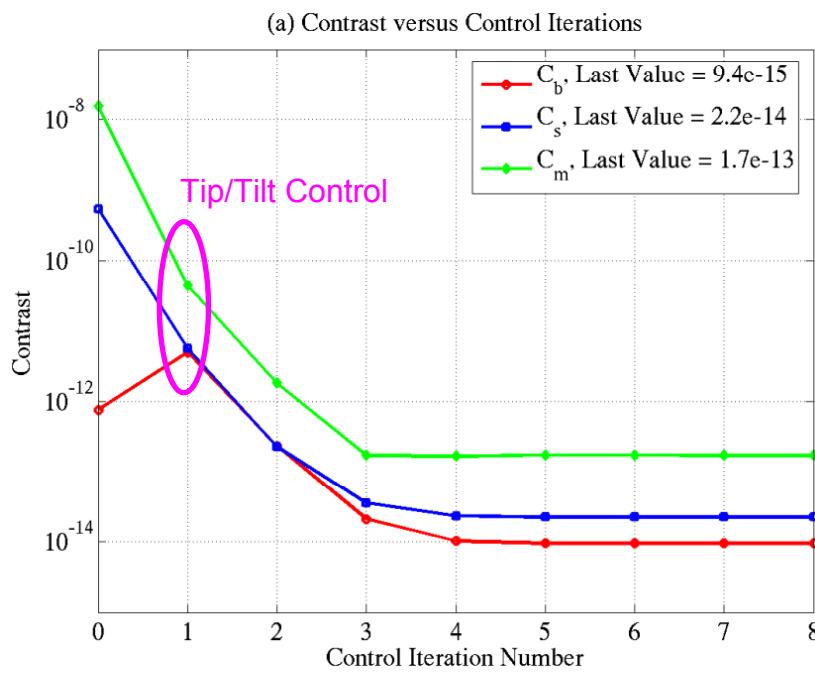
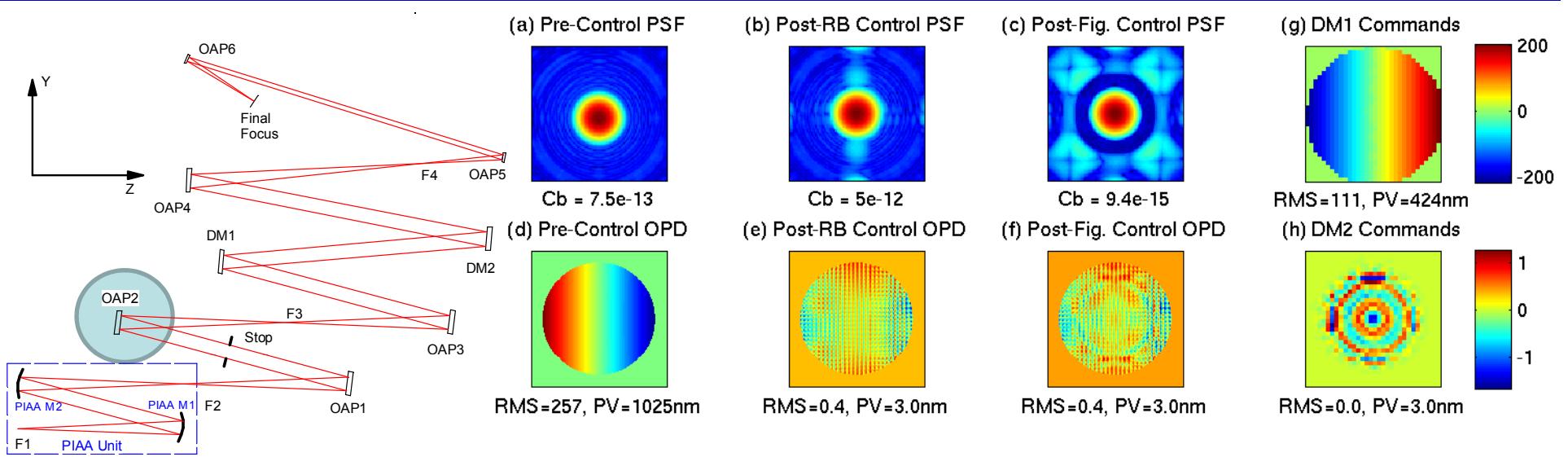


WFC Example (1) — Surface Errors

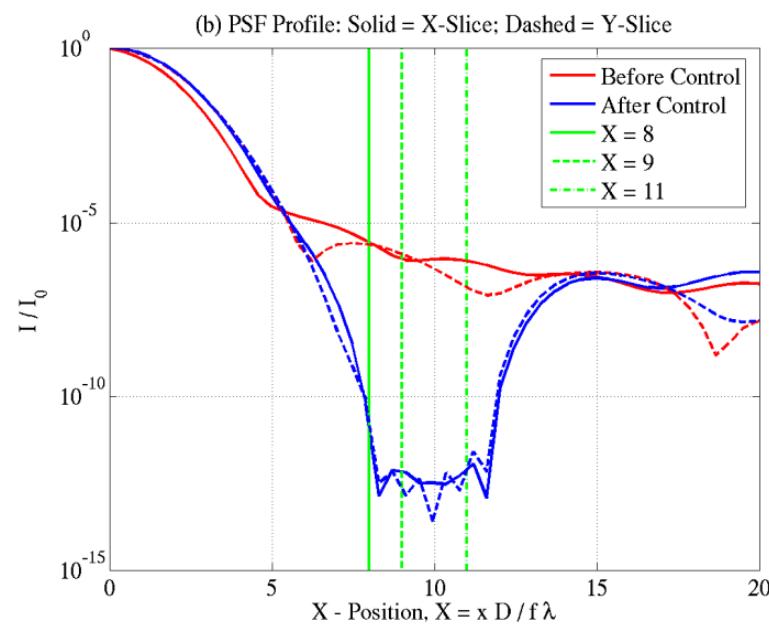
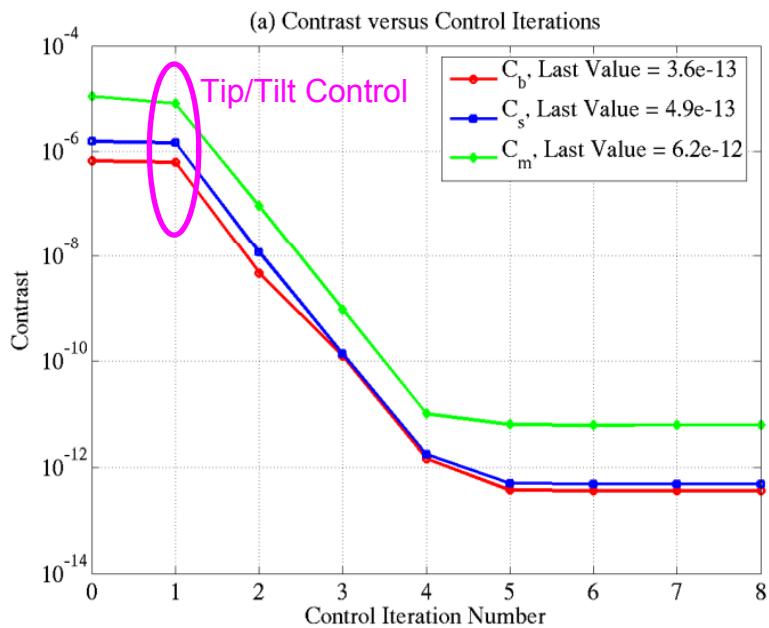
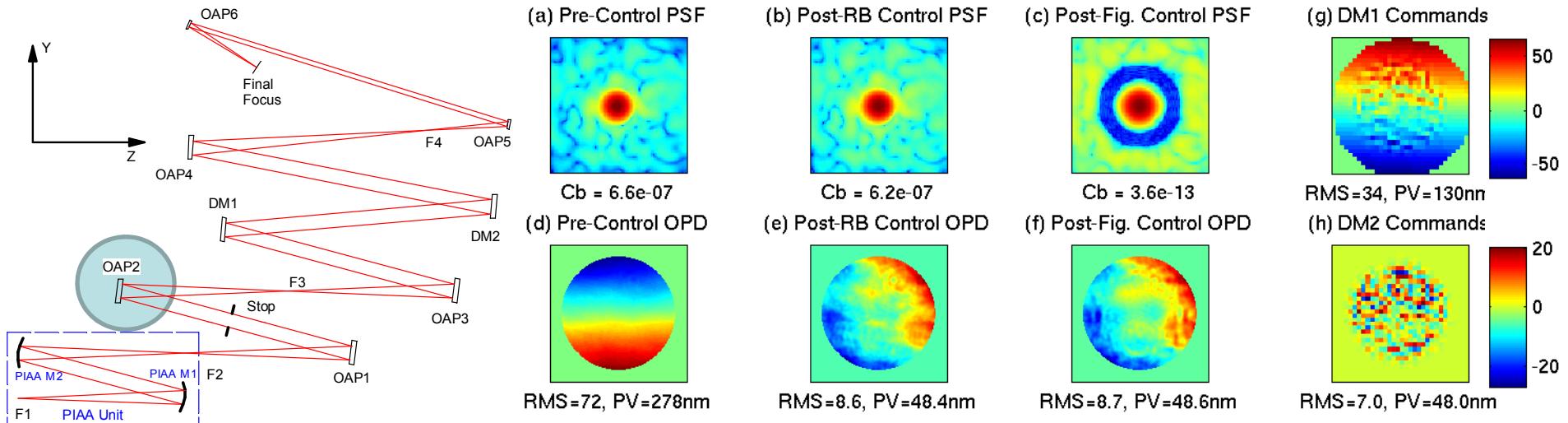
Used DMA figure error control only



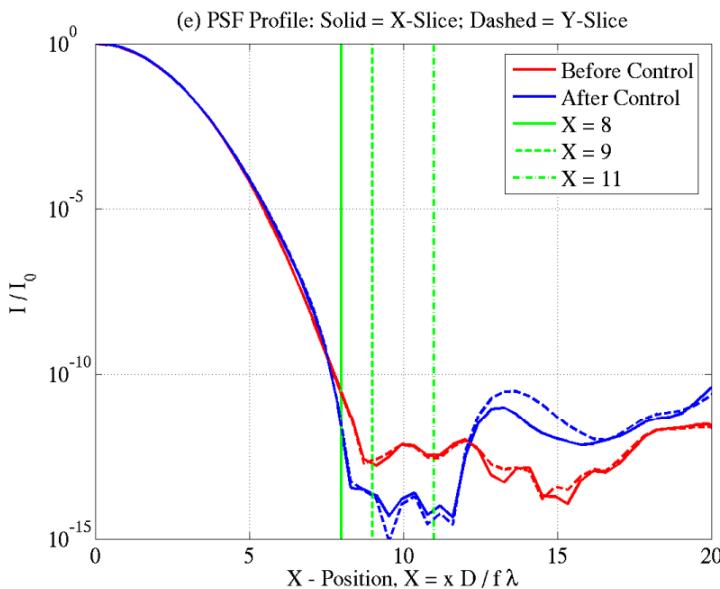
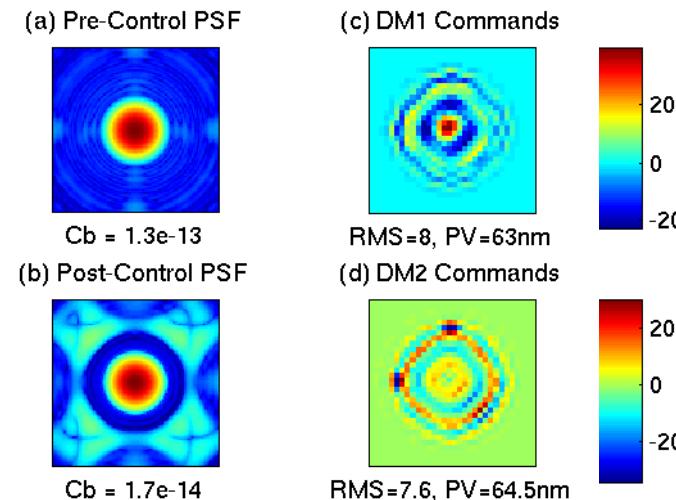
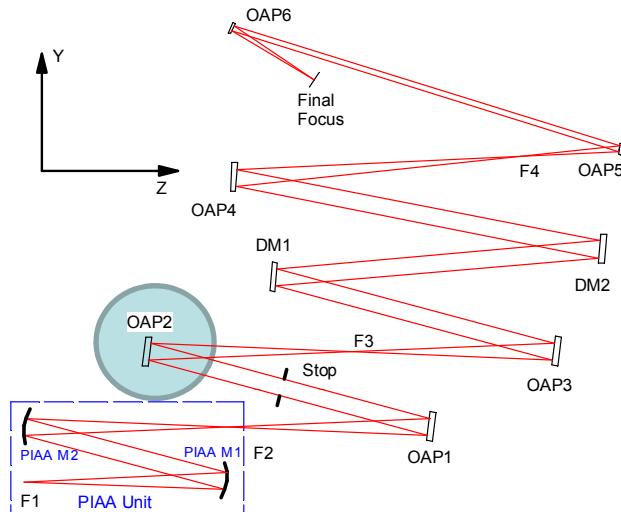
WFC Example (2) — OAP2 Rx = 20 μ rad



WFC Example (3) — (Fig. Errors)/2 plus OAP2 Tx = 5 μm

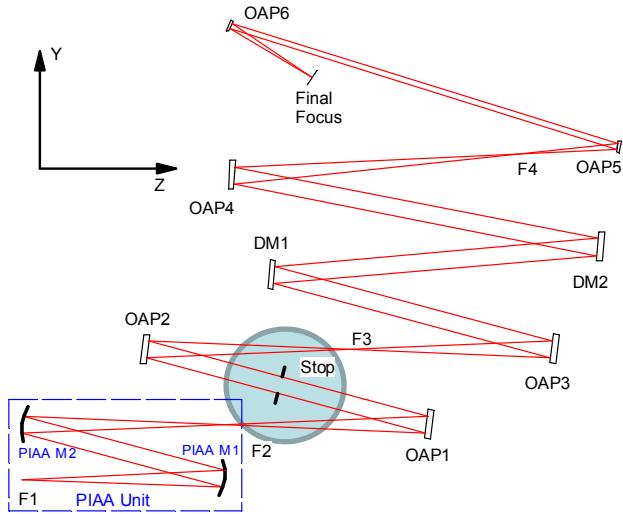


WFC Example (4) — OAP2 Focus Error: nm RMS = 35 nm



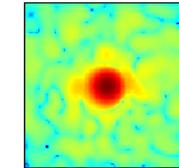
- Used single-step WFC—DMA figure error control

WFC Example (5) — Fig. Errors plus STOP Translation

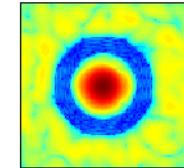


$T_x = 0 \text{ mm}$

(a) Pre-Control PSF

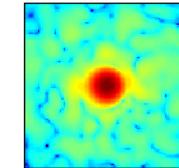


(b) Post-Control PSF

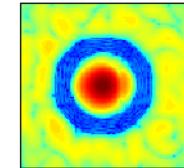


$T_x = 3 \text{ mm}$

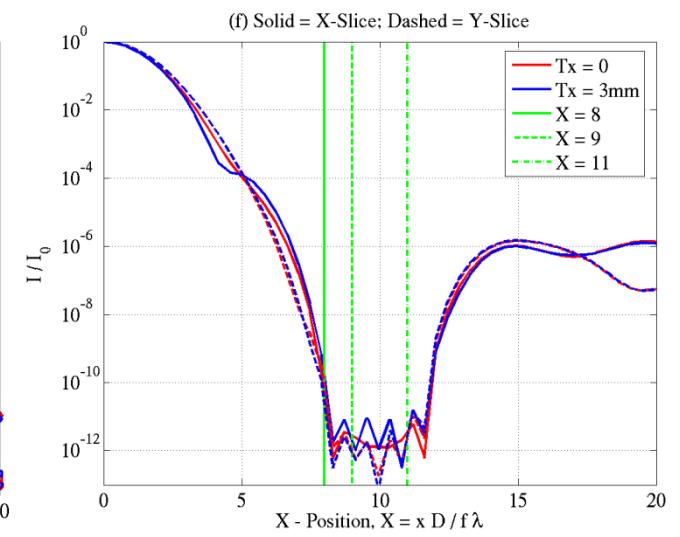
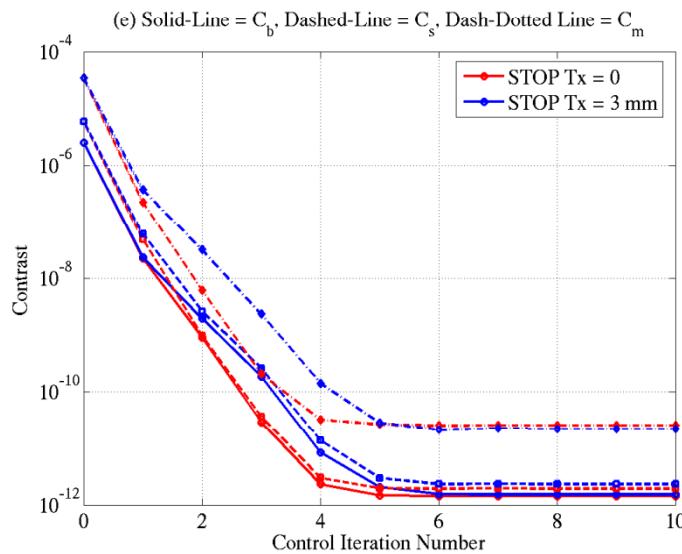
(c) Pre-Control PSF



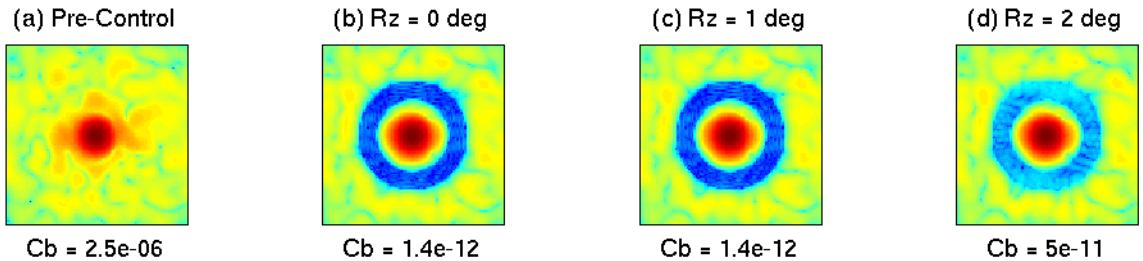
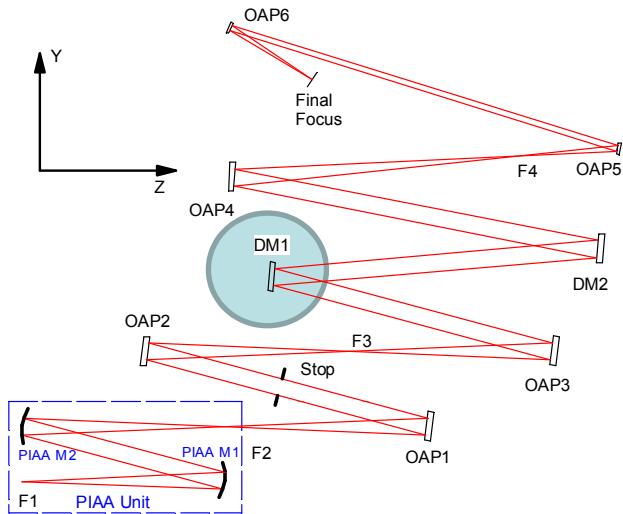
(d) Post-Control PSF



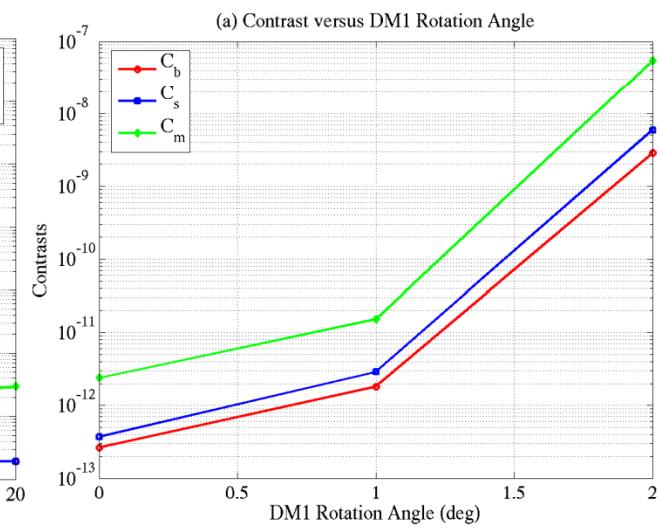
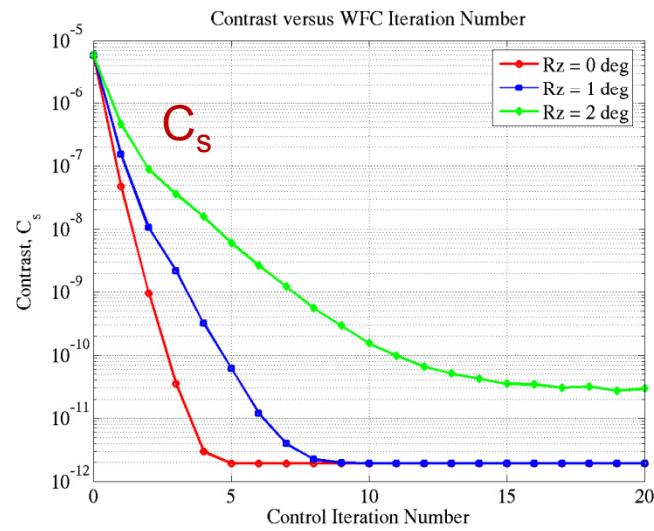
- STOP is translated after Influence Functions were calculated
- Used single-step WFC—DMA figure error control



WFC Example (6) — Fig. Errors plus DM1 Rotation



- DM1 is rotated in Local-Coordinates after Influence Functions were measured
- Used single-step WFC—DMA figure error control



1 deg = 17.5 mrad

Summary of Three Contrast Values

Case #	Error Source	Error Value	Remarks	C_b	C_s	C_m
1	Nominal		Before Control	9.4E-14	1.5E-12	1.1E-11
2	Figure Error	10 nm RMS	Before Control	2.5E-06	5.9E-06	3.4E-05
			After Control	1.4E-12	1.9E-12	2.5E-11
3	OAP2	$R_x = 20 \mu\text{rad}$	Before Control	7.5E-13	5.4E-10	1.5E-08
			After Control	9.4E-15	2.2E-14	1.7E-13
4	OAP2	$R_y = 20 \mu\text{rad}$	Before Control	6.4E-13	4.9E-10	1.4E-08
			After Control	8.3E-15	2.5E-14	1.9E-13
5	OAP2	$R_z = 150 \mu\text{rad}$	Before Control	5.2E-13	4.1E-10	1.1E-08
			After Control	8.4E-15	2.5E-14	1.8E-13
6	OAP2	$T_x = 20 \mu\text{m}$	Before Control	1.3E-12	8.7E-10	2.5E-08
			After Control	8.2E-15	2.4E-14	2.0E-13
7	OAP2	$T_y = 20 \mu\text{m}$	Before Control	1.3E-12	8.7E-10	2.5E-08
			After Control	1.8E-12	4.3E-11	4.9E-10
8	OAP2	$T_z = 200 \mu\text{m}$	Before Control	9.4E-14	4.3E-11	4.9E-10
9	Figure & OAP2 RB Errors	Fig. = 5nm RMS $T_x = 5 \mu\text{m}$	Before Control	6.6E-07	1.6E-06	1.1E-05
			After Control	3.5E-13	4.9E-13	6.2E-12
10	OAP2 Focus	35 nm RMS	Before Control	1.3E-13	3.6E-12	2.4E-11
			After Control	1.7E-14	1.0E-13	3.1E-13
11	Fig. = 10nm RMS plus STOP Tx or Ty	$T_x = 3\text{mm}$ $T_y = 0.5\mu\text{m}$	After Control	1.5E-12	2.3E-12	2.2E-11
			After Control	1.7E-12	2.8E-12	2.4E-11
12	DM1 Rotation	1 deg. 2 deg.	After Control	1.8E-12	3.7E-13	1.5E-11
			After Control	2.9E-09	5.9E-09	5.4E-08

Included in the paper

(Not presented today)

Summary

- Have implemented a MACOS-based simulation algorithm which
 - combines a ray trace, diffraction model, & a broadband wavefront control algorithm
 - is capable of performing full three-dimensional near-field diffraction analysis
- Investigated the effects of phase and rigid-body errors of various optics on the narrowband contrast performance of the PIAA/HCIT hybrid system
- Have shown that the 2-step wavefront control method utilizing 2-DMs is quite effective in compensating the effects of realistic phase and rigid-body errors of various optics
- Will investigate the broadband WFC/contrast performance, and non-ideal PIAA beams, in the future